Spatial associations between COVID-19 incidence rates and work sectors: Geospatial modelling of infection patterns among migrants in Oman

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Abstract

Migrants are one of the most vulnerable groups to infection with viruses due to the social and economic conditions in which they live. Therefore, spatial modelling of transmission of viruses among migrants is important for controlling and containing the COVID-19. This research focused on modelling spatial associations between COVID-19 incidence rates and migrant workers. The aim was to understand the spatial relationships between COVID-19 infection rates of migrants and the type of workplace at the sub-national level in Oman. Utilizing empirical Bayes smoothing (EBS) as well as the local indicator of spatial associations (LISA), six work sectors (health, agriculture, retail & business, administrative sector, manufacturing, and mining) were investigated as risk factors for disease incidence. The results indicated that the six work types each had a significant spatial association with cases of COVID-19. High rates of COVID-19 cases in relation to the workplace were clustered in the densely populated areas of Muscat. Similarly, high rates of COVID-19 cases were located in the north part of the country, along the Al-Batnah plain, where migrants are often employed in the agricultural sector. Further, COVID-19 migrants employed in the health sector was larger than for the other sectors. Therefore, working in the health sector can be considered a hotspot for the spread of COVID-19 infections. Due to a paucity of studies addressing the spatial analysis of COVID-19 associations with workplaces, the findings of this research are useful for decision-makers to set the necessary policies and plans to control the outbreak of the virus not only in Oman or the Gulf Cooperation Council (GCC) but also in other developing societies.

Key words: GIS; Spatial Associations, COVID-19 Incidence; Migrants, Work Sectors; Oman

1. Introduction

Efforts to control and alleviate the propagation of communicable diseases have been made on national, regional, and global scales (Chakraborty and Maity, 2020; Abulibdeh, 2020). However, efforts to reduce propagation of SARS-COV-2/COVID-19 have been hampered by several challenges, mainly the rapid transmission rate of the disease the nature of the virus associated with different socioeconomic and environmental variables (Shereen et al., 2020; Nicola et al., 2020; Gupta et al., 2020; Sohrabi et al., 2020; Li et al., 2020; Bourgonje et al., 2020). Studies have been conducted to understand the behavior of the virus, its detection, transmission, socioeconomic impacts, and treatment (Alzamora et al., 2020; Elmousalami and Hassanien 2020; Liu et al., 2020). For example, Zhai et al. (2021) utilised county-level data and geographically weighted panel regression to examine the spatiotemporal patterns of COVID-19 transmission across the U.S. There was clear spatial variation in the relation between COVID-19 transmission and socioeconomic and demographic factors. Moreover, population groups characterised by high incomes were more consistently associated low transmission rates. Similarly, Oyedotun & Moonsammy (2021) applied discrete and continuous panel regression and spatial lag models to examine the relationship between COVID-19 mortality and confirmed cases across the countries of South America. The modelling outcomes revealed that there was positive relationship between confirmed cases and population density, while there was a negative relationship between mortality and gross domestic product (GDP).

In their recent work, Budnitz & Tranos (2021) utilised data on individual broadband speed to investigate how the quality of internet services might influence the accomplishment of work from home during the COVID-19 lockdown in the UK. The study indicated from the temporal profile of broadband usage that seven out of nine clusters experienced slower upload speeds in the morning. This pattern of slow upload speed can be attributed to extreme telecommuting, particularly video calls, during the pandemic. In an analysis of the associations between staying at home during the COVID-19 pandemic and sociodemographic variables at the U.S. census block group (CBG) level, Huang et al. (2021) found a statistically significant correlation between home-dwelling time and economic status. In addition, poor communities stayed at home less compared to wealthy and rich communities, reflecting the luxury nature of stay-at-home mandates across all geographical zones. Analysing urban mobility during the COVID-19 lockdown, Kar et al. (2021) investigated spatial variation in essential travel in Columbus, Ohio during the pandemic-induced business closure. The findings showed spatial differences among socioeconomic groups in travel patterns. During the lockdown, and according to variation in spatial accessibility, moderate and high socioeconomic status travellers made large numbers of long-distance work trips while low socioeconomic status travellers made a small number of work trips.

Although no evidence has been confirmed yet that a certain group of the population is more vulnerable to COVID-19 infection, socioeconomic circumstances, living conditions and work sector have direct impacts on infection risks. Nevertheless, spatial studies that address the associations between disease transmission and demographic structure are still quite rare.

Rather than analysing the impacts of COVID-19 restrictions and lockdowns on economic sectors generally and migrant work specifically, the aim of this research was to examine the spatial associations between incidence rates among migrants and their work sectors at the subnational scale in Oman. Thus, the following research questions were answered:

- To what extent is there an association between COVID-19 incidence rates among migrants and working sectors?
- Which work sectors are spatially correlated with disease incidence rates?
- Where are areas of abnormally high incidence rates given underlying work sectors as risk factors?

2. COVID-19 and migrant populations

The incidence of COVID-19 in migrants is due to the complex interaction of socioeconomic factors, health determinants, potential genetic susceptibility, higher prevalence of underlying medical co-morbidities that lead to more severe disease, and/or barriers to accessing care (Khunti et al., 2020; Tai et al., 2020). Migrants are more at risk of exposure to COVID-19 disease due to crowded conditions both in residential dwellings and in workplaces. In some countries, overcrowd work environments and low access to protection measures may have led to increased exposure and hence migrant workers highly affected by the COVID-19 pandemic (HSU, 2020; Turcotte and Savage, 2020).

2.1 Working Conditions/Work Sectors and COVID-19

Migrant workers are typically employed in lower skilled roles and have low-income distributions, as many of them are overrepresented in lower socioeconomic strata, and hence they are forced to accept undesirable and low-status jobs (Sönmez et al., 2020). Other migrant workers may work in key services such as health care. A recent study investigated the infection and mortality rates of healthcare workers globally (Bandyopadhyay et al., 2020) and found that higher rates of infections were mainly among women and nurses while the large mortality was among men and doctors. In the same vein, Kasper (2020) reported higher prevalence of COVID-19 in health sectors.

The propagation of COVID-19 has posed a serious occupational health risk to healthcare workers because of their frequent exposure to infected individuals (Saqlain, 2020; Hoe Gan, 2020). Although healthcare workers may have better infectious disease protection plans than other occupational settings, they still face increased exposure to the disease and hence have higher likelihoods of being infected by the disease (Baker et al., 2020). However, these protection measures may not always be effective in protecting healthcare workers from infection, particularly when the number of incident cases is very high and hospitals are overwhelmed due to heavy patient loads (Brousseau, 2020). In Wuhan, for example, around 4% of confirmed COVID-19 incidents were in healthcare workers. This indicates that such workplaces are potential locations of transmission although the workers are trained to take measures and protect themselves from such hazards (Wu and McGoogan, 2020).

Depending on occupational characteristics, some workers are at increased risk of contracting the disease due to their direct interfacing with the public and other workers and hence are considered a nexus of disease transmission to the community. Baker et al. (2020) found that around 10% of workers in the USA were employed in occupations characterized by direct exposure to disease or infection at least once a week and 18.4% of them worked in occupations where infection or exposure to disease occurs once per month (Baker et al., 2020). These workers were employed mainly in the healthcare, protective service, construction and extraction, education, office and administrative support and community and social services occupations.

Migrants commonly face adverse work conditions with low-wage jobs and experience excess chronic stress, exacerbated by economic, political, and social inequities (Sönmez et al., 2020). Migrants can also be exposed to crowded working conditions, work with hazardous material, or work while they are sick due to social or economic pressure, which may result in the further transmission of the disease (Platt and Warwick, 2020). As a result, several cases were reported in many production plants, factories, and on farms primarily by migrant workers. Migrants have been found to be less likely to work in jobs that could be performed remotely and thus are more at risk of COVID-19 (Borjas and Cassidy, 2020; Abulibdeh, 2020).

Studies found that industrial workers were more susceptible to COVID-19 infection where underlying health problems (such as respiratory system problems and occupational diseases) were common among these workers (Quynh Nguyen et al., 2017; Pham et al., 2019; Tran et al., 2020). Furthermore, self-treatment was the most common method that these workers tended to use when having health problems (Tran et al., 2019). Tran et al. (2020) concluded that the spread of COVID-19 disease among industrial workers will cause more severe and life-threating conditions among migrants.

Hilson et al. (2020) investigated the effects of the COVID-19 pandemic on artisanal and small-scale mining (ASM) in sub-Saharan Africa. This sector employs more than 25 million people and creates significant economic opportunities indirectly. In particular, this study investigated how the communities dependent on ASM have been affected economically due to the changes made at the local, regional, and international levels because of the spread of the virus. Calvimontes et al. (2020) examined the impact of the pandemic on small-scale miners in different communities in Brazil. The study highlighted the capacity of miners to self-organize and find alternative solutions to cope with the pandemic. Miners in Brazil usually belong to heterogeneous social groups, and work without formal employment contracts (Calvimontes et al., 2020; de Theije, 2020). Despite the spread of the disease and the risk of being infected, economic gain is the main reason motivating miners to work, as they need to meet their financial responsibilities and basic needs. However, miners believe that they are safer in the mining site than in town in terms of the risk of disease contagion as they do not leave the mining sites very often and thus, they believe this is similar to self-quarantine. However, de Castro et al. (2020) found a disparity between the numbers of COVID-19 in some mining municipalities in Brazil but jobs in this sector remained stable throughout the pandemic compared to other sectors.

Farmworkers are another group of workers that are affected by the spread of the pandemic. For example, migrant farmworkers in the USA have closed work permits and face inequities, such as overcrowded living conditions, isolation, lack of access to field sanitation, difficulty accessing health care, lack of access to personal protective equipment, and inability to switch employers (Haley et al., 2020). These conditions further magnify the possibilities of being in an increased risk of exposure to the disease (Caxaj and Plamondon, 2020). Flocks (2020) investigated the impact of the COVID-19 pandemic on H-2A agricultural workers in the USA. This group of workers is more vulnerable to transmission of the disease because they have less control over their physical environment compared with domestic farmworkers. Despite the increased number of incidence cases in this group of workers, there was no rule in the US that addressed the need to protect workers' health because of the disease.

2.2 Living Conditions of Migrants and COVID-19

Most of the studies conducted in the USA and Europe investigated the effects of COVID-19 on undocumented migrants (Keller and Wagner, 2020; Wernly et al., 2020). In Europe, migrants are more likely to reside in places with high population density such as urban areas or migrant campuses (Costa and de Valk, 2018). Under these conditions, migrants are unable to follow basic mitigation and prevention practices such as hand hygiene, self-isolation, and social distancing. Therefore, the COVID-19 mitigation measures that most European countries are taking are difficult to implement in these areas (Maroko et al., 2020). Migrants may live in crowded multi-generational households due to cultural and economic reasons, which may increase the risk of disease transmission within households and hence mitigation measures such as social distancing or self-isolation are difficult. In the USA and the UK, migrant groups are categorized amongst vulnerable and marginalized populations with longstanding structural inequalities and complex socioeconomic health determinants (Greenaway et al., 2020; Openshaw and Travassos, 2020). The focus of these migrants living conditions have been on those living in refugee camps, reception centers and detention centers which are considered at high risk for COVID-19 infection (Greenaway et al., 2020; European Centre for Disease Prevention and Control, 2020).

Keller and Wagner (2020) studied the impact of illegal migrants detained by Immigration Customs Enforcement (ICE) in the USA in addition to the impact on the nation’s public health. The ICE system is well known for overcrowding, inadequate health care, poor sanitation, and the complexity of containing contagious disease. Therefore, implementing the COVID-19 mitigation measures in these facilities is not possible and hence the authors suggested that the ICE should release those detained migrants that pose no threats to public health and safety in order to prevent the spread of the disease (Keller and Wagner 2020).

2.3 Underlying Health conditions of Migrants and COVID-19

Migrants are a heterogeneous population with different cultures and various health needs and, in many countries, they face barriers to health care systems (Greenaway and Castelli, 2019). COVID-19 disease has been documented in refugee camps and among asylum seekers in many countries such as Portugal, Germany, the Greek mainland, and the UK (European Centre for Disease Prevention and Control, 2020). Migrants also may face difficulties in accessing the health care system due to poverty, racial discrimination, cultural and linguistic barriers, lack of entitlement to health care or sectors within the health system, and difficulties navigating the health care system. These migrant communities lack accessible and affordable healthcare (Hardy et al., 2012; Martinez et al., 2015), which is particularly problematic during the COVID-19 pandemic. Migrants in the US are also under- or uninsured which significantly limits their ability for early COVID-19 diagnosis, which is essential to optimize individual patient outcomes and to mitigate and prevent the transmission of the disease to other community members (Clark et al., 2020).

Wernly et al., (2020) investigated the cardiovascular disease (CVD) risk distribution and health literacy of migrants in Europe compared to the host population. They found that health literacy among migrants was lower than the host population and that the rates of CVD risk factors in some subgroups of migrants were higher. Furthermore, they found that health literacy and CVD risk factors were key components in managing the public health response during the COVID-19 pandemic. They concluded that migrants are both a challenge and opportunity in terms of the health care system. However, interventions to manage chronic disease, screen for risk factors, and increase health literacy among migrants could improve the long-term health care outcomes for them.

Several studies have investigated the links between COVID-19 infections and living conditions and the underlying health conditions of migrants. However, few have looked at the spatial relationships between COVID-19 infection rates and work sector in migrant workers compared to the wider population. Many studies in the USA and Europe have revealed major health inequities among migrants, ethnic and racial minorities. Social and economic determinants will strongly influence susceptibility to and health outcomes of COVID-19; therefore, it is crucial to understand these factors when investigating the effect of the COVID-19 pandemic on migrants in Oman and if the migrants are disproportionately affected by the pandemic. Spatial modeling of disease transmission among migrants is crucial to guide responses to the pandemic in practice. In this study, infection rates of the disease were correlated with employment sector using spatial models to investigate the links for six work sectors within Oman, a country that has a substantial migrant population.

3. Materials and methods

3.1 Study area

Oman is located in the far south-eastern corner of the Arabian Peninsula, with an area of 309,501 km² and is the second largest country after Saudi Arabia on the peninsula. The country extends from latitudes 16.40° –26.20° north and longitudes 51.50°–59.40° east. Oman is bordered on the north by the Strait of Hormuz, to the northeast by the Sea of Oman. On the east and south by the Arabian Sea while on the southwest by the Republic of Yemen. Oman also shares borders with the United Arab Emirates (UAE) in the north and west, and the Kingdom of Saudi Arabia (Empty Quarter) in the west (Fig.1).

In 2021, the total population was 4,507,323 and approximately, 61.10% (2,751,842) of them were Omani with migrant populations accounting for 1,755,481 (38.9%) (NCSI,2021). Administratively, the country is divided into 11 governorates and 61 Wilayats (states), with the Muscat governorate being the largest in terms of population size and comprising six Wilayats including Muscat City as the capital of Oman. In 2019, the largest population density was 355.4 person/km^2 in Muscat while the lowest density was in Al-Wusta governorate (0.6). The majority of migrants are concentrated in Muscat governorate (more than 850,000), while approximately 260,000 live in north Al-Batnah and slightly more than 200,000 population live in Dhofar governorate (Year book, 2020).

Oman is a capital rich and labor poor country, which is reflected in the high prevalence of migrant laborers. Currently, around 39% of the total population living in Oman are migrants (World Bank 2021), the majority of whom are from South Asia (India, Pakistan, Sri Lanka, Bangladesh) and Southeast Asia (Indonesia and Philippines). In Oman, migrants are pillars to several urban and rural economic sectors such as the agricultural, industrial and commercial sectors (Mansour, 2017). As a host country, Oman benefits economically from migrant labours in different aspects such as reducing wages, small businesses, and fostering entrepreneurial activities, particularly in unskilled jobs (Mansour, 2017). Oman relies heavily on importing foreign labourers from different countries mainly because of the small size of the Omani population. Furthermore, due to cultural perspectives, the percentage of local women entering the workforce is low and hence the country relies on expatriate women, particularly in household jobs from South and Southeast Asian countries such as India, the Philippines, Sri Lanka, Indonesia, and Bangladesh (Mansour, 2017; Fernandez, 2010, 2011; Willoughby, 2006; Shah, 2004a, 2004b). Therefore, migrants are changing the population structure and the socioeconomic status and contributing to transformational development in the country.

The migrant workforce in Oman works mainly in construction, food services, manufacturing industries, healthcare and accommodation. These types of jobs are essential and often require workers to attend the workplace in-person as the jobs do not lend themselves to working from home. Furthermore, migrants are more likely to live with multiple roommates or with multigenerational family groups. Usually low-skilled migrants live in housing units that are characterised by overcrowding and low-quality infrastructure meaning that social distancing and self-isolation are difficult (David, 2009).

Following the onset of the COVI-19 pandemic, Oman implemented strict measures and restrictions to lessen the transmission of the disease. However, the incidence rate has increased since the first confirmed registered case on 28th of February 2020 to reach 133,728 confirmed cases with almost 26,000 cases per million as of January 2021 (Worldometer, 2021 – end January 2021). Few studies have been conducted to investigate the spatial distribution of the disease in Oman. Mansour et al. (2021) investigated the spatial variation of the relationship between the infection rate and different sociodemographic factors such as population density, age structure, hospital beds, long-term illness, and nurse practitioners. The findings revealed that for people aged 65 years and above, hospital beds, population density, and diabetes rates were statistically significant determinants of COVID-19 infection rate. Al-Kindi et al. (2020) performed spatiotemporal analysis to investigate the spatial patterns of the propagation of COVID-19 disease in Oman using five geospatial techniques. They assessed the spatiotemporal patterns of COVID-19, and quantified temporal differences in the rate of incidence. They found that the disease moved from the northeast of the country to the northwest and southwest and that the infection rates increased in the most populated areas.

In Oman, particular areas within the country have demonstrated high rates of COVID-19 cases (Mansour, 2021; Al-Kindi, 2020). Nonetheless, no studies conducted on the relationships between COVID-19 and migrants' employment in Oman nor GCC countries. These studies focused on the socioeconomic factors of migrants, particularly non-documented migrants. However, this literature did not consider the spatial patterns of COVID-19 among migrants. This gap is a major impediment to designing effective tailored interventions for this group of the population. Furthermore, although some studies investigated the impact of COVID-19 on migrants, no studies employed spatial techniques to assess the spatiotemporal characteristics of the spread of the disease on migrants. Such an investigation is crucial to quantify the spatiotemporal patterns of COVID-19 propagation across the country in general and among migrants in particular to determine the different demographic and socioeconomic factors that could accelerate transmission and incidence rates. Investigating the spatiotemporal incidence of COVID-19 is crucial in understanding the dynamics, occurrence and spread of the disease. As part of this, it is important to investigate the spatial impact of COVID-19 disease on migrants in the country considering their socioeconomic characteristics.

Migrants in Oman work in several public and private sectors. Table 1 illustrates descriptions of the calculated risk factors, the dependent variable and the source of each variable.

Figure 1 the study area and subnational administrative boundaries of Oman

Table 1 Descriptions of risk factors and data sources

Variable	Description	Source
COVID-19 incidence rate among migrants	The COVID-19 cases in each Wilayat calculated by dividing the total number of cases by total number of migrants.	MOH, Oman
Migrants' workers in health sector	The percentage of migrants working in health sector in each Wilayat calculated by dividing the total workers in this sector by the total migrants' workers and multiplied by 100	NCSI, Oman
Migrants' workers in retails &business	The percentage of migrants working in retails &business in each Wilayat calculated by dividing the total workers in this sector by the total migrants' workers and multiplied by 100	NCSI, Oman
Migrants' workers in administrative sectors	The percentage of migrants working in administrative in each Wilayat calculated by dividing the total workers in this sector by the total migrants' workers and multiplied by 100	NCSI, Oman
Migrants' workers in agricultural activities	The percentage of migrants working in agricultural activities in each Wilayat calculated by dividing the total workers in this sector by the total migrants' workers and multiplied by 100	NCSI, Oman
Migrants' workers in manufacturing	The percentage of migrants working in manufacturing in each Wilayat calculated by dividing the total workers in this sector by the total migrants' workers and multiplied by 100	NCSI, Oman
Migrants' workers in mining	The percentage of migrants working in mining in each Wilayat calculated by dividing the total workers in this sector by the total migrants' workers and multiplied by 100	NCSI, Oman

MOH: *Ministry of Health in Oman*. NCSI: *National Centre for Statistics and Information*

3.2. Methods

The excess risk of COVID-19 incidence can be defined as the number of infected people during the pandemic above and beyond what would be expected under normal circumstances. Spatially, in this research, we are interested in how the incidence rate of COVID-19 among migrants in each Wilayat varies compared to the national average. The COVID-19 incidence rate (R_{cov_i}) among migrants was computed as follows:

$$R_{cov_i} = \frac{x_{cov_i}}{p_i} * 10{,}000$$

Where $\boldsymbol{x_{cov_i}}$ indicates the reported cases of disease incidence among migrants in Wilayat $\boldsymbol{i}$ while $\boldsymbol{p_i}$ refers to the total migrants' population in Wilayat $\boldsymbol{i}$.

3.2.1 Empirical Bayes Smoothing

To stabilise COVID-19 incidence rates for Wilayats with small population sizes or low number of disease cases, Empirical Bayes Smoothing (EBS) was utilized. The main assumption was that the relative risks of population residing in Wilayat $\boldsymbol{i}$ **(**$\boldsymbol{\delta_i}$**)** were independently and symmetrically distributed according to a Poisson distribution:

$$x_i/\delta_i \sim Poisson\ (N_i \delta_i)$$

Where $\boldsymbol{x_i}$ is the random variable illustrating disease count in Wilayat $\boldsymbol{i}$ while $\boldsymbol{N_i}$ refers to the expected count for the same zone. The Empirical Bayes Smoothed (EBS) relative risk of $\boldsymbol{R_{cov_i}}$ borrows the neighbouring Wilayat rates to adjust the uncertainty rates as per the expression:

$$\hat{R}cov_i = \emptyset R_{cov_i} + (1 - \emptyset_1) m \delta_i$$

Where $\delta_i$is the ratio of prior variance to the data variance, while $m\delta_i$ is the prior mean (weighted mean). The final EBS rates remains virtually unchanged for all Wilayats with relatively large sizes of populations or numbers of cases (Nyadanu et al.,2019; Sankoh et al,.2002,). Applying the spatial empirical Bayes (SEB) smoothed rate, spatial patterns of the disease among migrants were mapped and visualized (Figure 2**)**. Unlike the raw rates, this empirical Bayes technique derives strength from neighbouring zones substantially to minimize the effects of small populations at infection risks within specific zones.

3.3.2 Local Moran's *I* and Local Indicators of Spatial Association (LISA)

The Local Moran's *I* is a measure of spatial clustering of a geographical variable where similar and dissimilar values cluster (Moran,1950). Giving the assumption that a linear relationship exists, Moran's *I* is utilized specifically to identify geographical units (Wilayats) and their neighbours where the deviations in the relationships among a variable's observations are minimum or maximum. The local Moran's *I* for spatial association is calculated as:

$$I_i = x_i = \frac{x_i - \overline{X}}{m_2} \sum_j w_{ij}(x_i - \overline{X})$$

$$m_2 = \frac{\sum_j (x_i - \overline{X})}{n}$$

Where n denotes the total number of observations (geographical zones)

$\boldsymbol{X_i}$ illustrates the attribute value of a feature $\boldsymbol{i}$ (geographical zone or Wilayat) in the considered variable and $\overline{X}$ refers to the mean value of that variable. $\boldsymbol{w_{ij}}$ is a calculated spatial weight between features $\boldsymbol{i}$ and $\boldsymbol{j}$ based on neighbouring status and m_2 is a constant for all locations.

The outcome value of Moran's *I* ranges from +1 (denoting positive autocorrelation and clustering) to -1(indicating negative autocorrelation and dispersion). The outcomes of the analysis involve four categories of similar and dissimilar observations clustering. The first category is ***high-high*** values which includes high values (above the variable mean) clustering with other high values. The second group is the ***low-low*** values which refers to a clustering pattern where low values (below the variable mean) cluster with other low values. These two categories (HH and LL) signify a positive spatial correlation. The remaining two groups comprise the ***high-low*** group which demonstrates high values clustering with neighbouring low values (below the variable mean). The last group is ***low-high*** values where low observations cluster with surrounding high values. These two groups (HL and LH) show a Negative Spatial Autocorrelation and illustrate dissimilar values (outliers) (Anselin, 1995).

3.4.3 Bivariate local indicators of spatial association (BiLISA)

The BiLISA is an explicit generalization of the concept of spatial association in which the measure relates the value of a variable at a specific zone to that of a different variable at the neighbouring zones. To measure the local relationship between the COVID-19 incidence rates among migrants and a set of variables representing work sectors, BiLISA was calculated as follows (Anselin,1995):

$$\mathrm{Bi}_{1,2} = x_1^i \sum_{j=1}^{n} w_{ij}\, x_2^j$$

Where $\boldsymbol{Bi}_{1,2}$ refers to the bivariate value of the variable **1,2** at spatial unit ***i*** while *n* represents the total number of Wilayats. $\boldsymbol{x_1^i}$ indicates the degree of linear association between the values of variable **1** (x) at a specific neighbourhood i. x_2^j signifies the mean value of the second variable in neighbouring spatial zone j and w_{ij} is the spatial weight between the ith and jth spatial units.

To create bivariate maps, a spatial weight matrix was developed on the basis of first-order queen zone contiguity. Given the size and irregular shapes of Wilayats polygons, the queen matrix is suitable for capturing spatial autocorrelation and disease. Weights were assigned to all Wilayats that share common edges and corners where $\Sigma w_{ij} = 1$ if Wilayat i and j shared a common boundary; otherwise $\Sigma w_{ij} = 0$, for non-neighbouring Wilayats.

4. Results

In this research, we were interested in finding out how the incidence rate of COVID-19 amongst migrant workers was related to the national average and how it correlated with job type. The spatial distribution of incidence rates (Fig. 2) shows that COVID-19 incidence rates varied across the country with the largest numbers in the northern regions, particularly Muscat governorate and urban Wilayats (Muscat, Matrah, Bowsher, and Al-Seeb). This is due mainly to population concentration and overcrowding of migrants' housing units, particularly in urban districts. Similarly, larger averages are found in the far north within Al-Burmai and parts of North Al-Batnah governorates. The large averages were spread sparsely over the eastern coasts and a clear Eastern excess was apparent along with Jaalan Bani Bu Ali, Al-Duqum , Al-Jazir, and rates were high in Sadah and Maribat. Most of the migrants living in regions such as Al-Duqum are low-skilled migrants (Mansour, 2017) and lack affordable housing and thus they live in crowded conditions and in close proximity where protective measures and social distancing are difficult to enforce. Accordingly, workers who live in such circumstances are at high risk of COVID-19 infection. The low rates were observed mainly in the interior Wilayats of North Al-Batnah (e.g Bidiya, Al-Qabal, Wadi Bani Khalid, and Jaalan Bani Bu Hassan). These places are characterised as mountainous environments with low percentages of migrants who work mostly in the agricultural sector or in domestic work. The spatial distribution of high and low incidence areas was less heterogeneous in rural and desert areas than coastal areas.

A bivariate map shows the COVID-19 rates among migrants and locals (Omani populations) across subnational administrative zones (Figure 3). There were marked spatial differences in the incidence rates between migrants and locals across the study area. The lowest rates among migrants were seen in the middle part of Al-Dakhalia governorate (e.g., Bahle wilayat) and a strip from the northeast to the south. On the other hand, the lowest rates among locals occurred mainly in internal Wilayats in the West of the country. In essence, these Wilayats are described by suburb and rural residential areas with a low number of migrants workers. The majority of workers work in small business properties such as groceries, retail stores, shops, and cafes and they live in single rooms and less crowded housing units.

Figure 2 spatial distribution of bayes rates of COVID-19 incidence among migrants across the study. The dark blue colour indicates areas with higher rates among Omani populations relative to migrants

Figure 3 Bivariate map of COVID-19 incidence among migrants and Omani populations across the study. The dark red colour refers to areas with higher rates of migrants compared to Omani people.

4.1. Associations of work sectors with COVID-19 incidence rates

Studying spatial transition mechanisms among migrants' communities in Oman requires analysing the relatedness between disease infection rates and working sectors and workplaces of migrants' populations. Several maps of excess COVID-19 incidence rates among migrants were created utilizing work sectors as a base while the infection cases of migrants were used as an event base (Figure 4). Six factors illustrated statistically significant spatial correlation with COVID-19 incidence rates. Using the percentage of migrants working in the agricultural sector as a base, higher than expected rates were found mostly across the northern Wilayats of both Muscat (e.g. Al-Seeb and Matrah) and North Al-Batnah (e.g. Sohar and Liwa) governorates. Likewise, other Wilayats that show greater incidence than expected were in the middle part of the country particularly Al-Wusta governorate as well as the south-western parts of Dhofar governorate (Sadah, Mirbat, and Taqah) (Figure 4a). The spatial distribution of excess disease incidence among migrants for health and social work sectors indicates that mostly the urban Wilayats within Muscat and Al-Batnah governorates experienced higher than expected incidence as compared to the average national rate (Figure 4b).

For migrants working in the administrative sector a low number of Wilayats (11) had greater than expected incidence and these were predominately in the Muscat urban areas, Al-Duqum in Al-Wusta governorate, and Adam in Al-Dakhliya governorate (Figure 4c). Considering the retail and business sector as a risk factor determining COVID-19 incidence, most of the Wilayats located in the northwest showed higher than expected averages compared to the national average (Figure 4d). Similarly, some Wilayats in the southeast (e.g. Al-Duqum, Al Jazir, and Mirbat) had higher than average incidence rates. A cluster of zones extends from the northeast to south (Al-Qabil, Bidiyah, and Mahawt) associated with below average incidence rates.

Migrants working in the manufacturing sector were associated with increased excess risks in all administrative zones of Muscat governorate and along Wilayats in the Al-Batnah coastal plain (Figure 4e). Likewise, a few places along the east and south coasts showed also large incidence rates such as Al-Duqum, Al Jazir, and Salalah. On the other hand, a clear belt from north to south (Al-Qabil to Mahawt) was apparent along the northeast part of the study whereas this cluster mirrors low incidence rates. For migrants working in the mining sector, a few Wilayats experienced high incidence rates of the disease particularly Al-Seeb in the north and Salalah in the south (Figure 4f). A cluster of low incidence rates can be seen in the northeast part of the Country and most Wilayats had infections rates less than the national average.

Figure 4 Spatial distribution of excess COVID-19 incidence rates among migrants in Oman with respect to the work sectors factors as base covariate, indicating Wilayats that have infection rate greater than expected incidence: Agricultural sector (a); health and social sectors (b); administrative sector (c); retails and business (d); manufacturing (e); mining (f).

Table 2 Bivariate Moran's *I* of the significant risk factors of migrant workers in job sectors

Risk factors	Bivariate Moran's I	Pseudo p-value	z-value
Agricultural activities	-0.0172	0.004	-2.360
Retail & business	0.2917	0.003	3.996
Health sector	0.4144	0.002	5.341
Administrative sector	0.4101	0.002	5.152
Manufacturing	0.4119	0.000	6.116
Mining	0.2612	0.013	3.376

A disease conditional map (Fig. 5) shows that high percentages of workers in retail-business and manufacturing together were associated with high COVID-19 incidence rates in mostly Wilayats located in the north and northwest (upper right map). Whereas, the lower rates of disease infection were in the south. The lowest incidence rates also cluster in a strip from northeast to the south. The number of locations with emerging

COVID-19 incidence conditioned on retails-business and manufacturing were detected in the upper left panel where manufacturing was high with low retail & business.

Figure 5 COVID-19 incidence conditioned on manufacturing and retail business where Wilayats with relatively high rates due to co-location of the two risk factors were represented using the brown colour while the low rates are in light blue.

3.3. Spatial autocorrelation and cluster-outlier detection (bivariate LISA)

The bivariate LISA maps in Figure 6 show spatial patterns of the statistically significant associations between COVID-19 incidence rates among migrants and a set of risk factors across the subnational boundaries in Oman. The results illustrate that there was a hotspot and positive autocorrelation (high-high) between COVID-19 incidence rates and percentage of migrant workers employed in the agricultural sector specifically in North Al-Batnah governorate as well as Al-Duqum Wilayat (Figure 6a). Positive autocorrelation (low-low) clustering was found in the northeast of Dhofar governorate. Two further clusters associated with workers in agriculture (high-low and low-high) can be observed. The high-low cluster (Wilayats with high disease incidence rates surrounded by Wilayats with low percentages of migrants' workers in agriculture) was formed by Wilayats of Jaalan Bani Bu Hassan in the east and Mahadah and Yanqul in the east. The low-high cluster (Wilayats that had low disease incidence rates surrounded by areas with high percentages of workers in agricultural sectors), was found only in the south and composed of Wilayats Al Mazyunah, Rakhyut, and Salalah.

Figure 6b shows the map of the spatial association of clusters between disease incidence rates and migrants' workers in the retail-business sectors. Three positive or hotspot spatial clusters (high-high) appeared in different locations. The first cluster was found in the north region (urban zones within Muscat governorate) including Al-Seeb, Muscat, Bowshar and Matrah. The second cluster was formed by Wilayats of Bahla, Manah, and Nizwa. Two coldspot clusters (low-low) were found in the northeast (Ibri) and the south (Al Mazyunah, Rakhyut). A high-low cluster type was found in the northern region of Al-Dakhaliya governorate (Bidbid and Samail) as well as Muqshin while a cluster of low-high was found in the central part of the country.

The association between disease incidence rates and migrants' workers in the manufacturing sector is depicted in Figure 6c. Administrative zones of positive spatial association (high–high) were located in Al-Seeb and Bauwshar (within Muscat governorate), Sohar in the north, and Al-Duqum in the central east of the study. Cold spots comprise a spatial cluster of low–low were located in the Mauhuat and Sadah Wilayats. Figure 6d represents the relationship between incidence rates and migrant workers in the health sector. Positive autocorrelation pattern (high–high) was observed in the north, especially in urban zones (Al-Seeb, Bauwshar, Matrah, Barka and Muscat). The spatial pattern of cold spots (low–low) appears mostly in the far north and northwest. A few statistically significant (at the 0.05 level) high-low wilayats (outliers) occuredin the north of Al-Dakhaliya governorate (Bidbid). This pattern demonstrates that a high prevalence of COVID-19 among migrants coexisted with migrant workers in the health sector.

For the association between disease incidence rates and migrants' workers in the administrative sectors (Figure 6e), our results showed three high-high cluster types in Al-Seeb and Barka in the north, Adam and Bahla in Al-Dkhaliya governorate, and the southwest of Dhofar governorate (Sadah and Mirbat). The low–low clusters were found in the east of Dhofar governorate (Thumrayt and Muqshin). On the other hand, outlierclusters (high-low and low-high) can be observed in the north (Ar Rustaq, Ibra, and Samail) and the far South (Al Mazyunah and Dalkut), respectively. The high association between disease incidence rates and migrants' workers is spatially concentrated in the north (Sohar, Al-Seeb, and Bowsher) and in the east (Al-Duqum) (Figure 6f). In contrast, a cold spot (low–low) pattern is observed in the northwest part of the country (Ibri, Bahla, and Adam).

Figure 6 Maps of Local indicators of Spatial Association (LISA) bivariate clusters of COVID-19 incidence rates among migrants with migrant workers in 6 sectors: Agriculture sector (a) retails-business sectors (b) manufacturing sector (c) health (d) administrative sector (e) mining sector (f). Hotspot (High-High), Coldspot (Low-Low), and outliers (High-Low & Low-High). The statistical inference based on Monte Carlo randomisation test at 999 permutations, showing significant pseudo $p < 0.05$ clusters.

5. Discussion

Although a considerable body of existing literature has addressed the interrelationships between COVID-19 and migrants (Turcotte &Savage, 2020; Keller and Wagner, 2020; Wernly et al., 2020; Greenaway et al., 2020; Openshaw & Travassos, 2020), spatial studies on the associations between migrants work sectors as risk factors, and disease incidence rates have not been conducted. Accordingly, this research represents a novel contribution to the evidence base concerning associations between employment sectors of migrants and COVID-19 incidence. It also offers useful insights regarding the spatial autocorrelation and spillover of the disease among migrants in Oman. Furthermore, it represents a novel linkage of a wide range of health, socioeconomic and epidemiological fields. Although migrants, especially low skilled workers, play an essential role in the response to the COVID-19 pandemic through working on the frontlines, they may be some of the most affected and most vulnerable populations to disease infection (Claudia, 2020).

The findings from the analyses showed that six main variables (migrants working in employment sectors) were strongly associated with spatial variations in excess COVID-19 incidence across Oman. The spatial clustering of high COVID-19 incidence and their relationship with work sectors is clear in urban Wilayats within Muscat governorate as well as Al-Batnah coastal plain. This can be attributed to the demographic characteristics of these areas where large number of migrants are concentrated and working in several public and private sectors such as commercial properties, agricultural farms, shops, shopping centres, warehouses, factories, medical centres and hospitals.

In this research, the main focus was on the recognition of the workplace as a COVID-19 infection risk. We found a number of risk factors with significant associations with COVID-19 incidence rates in Oman. The significant autocorrelation between these factors and disease incidence among migrants indicates that these factors might be indispensable predictors of infection occurrence at the subnational level. Considering the percentages of migrants working in agriculture, high rates of COVID-19 incidence were found in the north of the country particularly along the Al-Batnah plain. This pattern might be explained by the fact that the low wage farmworkers in this sector face challenges to afford the required prevention and measures such as isolation, social distancing and disinfectant. In addition, low skilled workers in rural and desert areas often have relatively poor knowledge about the disease prevention with low access to health facilities. Consequently, high percentages of migrants working in agricultural activities and operations were associated with greater levels of COVID-19 incidence rates across local communities. Our findings indicated that the prevalence of COVID-19 among health and medical workers was significantly higher than for others sectors which is consistent with previous studies, (Kasper,2020; Godderis, 2020). Accordingly, jobs in the health and medical sectors can be classified as presenting high or very high exposure risks to COVID-19 infection. Most excess disease incidence among migrants working in health and medical sectors were in urban zones within Muscat and Al-Batnah in the north and Al-Duqum in the east. The high stress of patient loads in hospitals and clinics makes workers in these sectors particularly vulnerable to infection. LISA analysis revealed that the bivariate clustered zones with High-High positive spatial association for COVID-19 incidence and migrant workers in the health sector were located around the capital Muscat, as well as Barka Wilayat in South Al-Batnah. Local clusters of negative spatial association Low-High in the south and southeast.

Cluster detection also identified four clusters exhibiting positive autocorrelation between disease incidence and workers in the manufacturing sector in the north, within Muscat governorate and in the northwest around Sohar Wilayat, and Al-Duqum in the east. In addition, spatial association was found between COVID-19 incidence rates among migrants and percentages of migrants working in administrative sectors. Positive associations (High-High) were found mainly in the urban areas of Muscat governorate. The high Covid-19 incidence rates in this cluster can be explained by the fact that large number of migrants are working in public and private establishments and organizations within Muscat governorates and the majority live in overcrowded housing. We identified three hotspot (high-high) clusters of the association between workers in the retail and business operations and disease rates. These clusters included 10 Wilayats located in the north and south of the study area with incidence rates higher than the national average surrounded by other zones with higher than average rates.

This can be attributed to the fact that most retail stores, including drug stores, grocery stores, and other entities that sell essential supplies, and businesses in the informal sector, remained open during the COVID-19 pandemic, particularly those with high customer volumes.

This research could provide effective information to decision makers by identifying disease infection hotspots that are associated with workplace relative risks. Consequently, precise measures, prevention and control of the disease can be implemented. The ramifications of lockdown and social distance restrictions will be felt for months, if not years, particularly for migrant workers within their work systems. Despite appearing to be at the first stage of disease receding and vaccination programmes beginning, migrant workers remain the most vulnerable groups to infection.

The spatial aspect of COVID-19 associations with workplaces has not been studied, but it can provide vital information for the effective interventions that target protecting workers from disease infections in local areas. In the absence of individual-level data of COVID-19 infection, particularly across the developing nations, aggregated area-level variables are often the only source of information to investigate how factors associated with disease incidence may contribute to understanding infection patterns and risk mitigation. Workplace sectors of migrants have been identified as potential determinants of COVID-19 incidence rates among migrants at the subnational spatial scale. As a result, policy makers and governmental planners need to address geographically the associations between disease transmission and workers in each economic sector ,particularly with the lifting or loosening of lockdown restrictions. To reduce infection risk exposure within workplaces, the implementation of administrative control is required which includes several procedures and measures such as excluding sick workers and visitors, appropriate social distance and cleaning and disinfection policies.

Data at the household or individual-level were not available, and ,therefore, this study was limited by the utilized aggregated dataset at the zonal subnational level. Accordingly, the explanations of the results should be interpreted with caution to avoid the risk of ecological fallacies. In addition, we included only the risk factors that are associated with job sectors and workplaces while several risk variables that might be interrelated to COVID-19 incidence were not considered due to data availability.

An understanding of the associations between the disease incidence and migrant workers is indispensable to control the spread of the virus, specifically among workers within workplace environments. The results of this study showed that migrants working in the health care system in the capital city of Muscat are infected by the disease at a high rate, while more cases were found among migrants working in the agricultural sector in Al-Batinah area. This reflects the economic characteristics of these two areas and how migrant workers in these areas are impacted by working and living circumstances. Furthermore, the spatial distribution of migrants based on workplaces resulted in differences in the spatial distribution of incidence between migrants and Omani citizens across the country. Migrants in the country have the right to access the health system similarly to Omani citizens; however, the type of work that migrants occupy and the associated social characteristics maybe the main determinant of the increased number of cases amongst migrants. Decision- makers may need to implement different mitigation measures where migrants are clustered to slow down the spread of the disease.

6. Conclusion

Oman is major importers of migrant workers in the region and globally. The dominance of migrants is more pronounced in the workforce than it is in the total population and hence migrants are major contributors to the economic prosperity of the country. Migrants in Oman work in many economic sectors and are distributed in different areas of the country. The socioeconomic conditions of migrants in Oman and the region make them more vulnerable and at high risk of suffering from the COVID-19 pandemic. Therefore, the aim of this study was to model the spatial distribution of the COVID-19 among migrants based on the type of workplace to understand the spatial relationships between migrant infection rates of COVID-19 and their workplace.

Our analysis emphasizes the associations between percentages of migrants in their workplaces and disease incidence at subnational and finer scale. The increased percentages of migrant workers in the agricultural, health and business sectors were associated with an excess of COVID-19 incidences mainly in Muscat and Al-Batnah governorates. Similarly, migrant workers in manufacturing and mining were associated with increased risk of COVID-19 incidence rates in the east particularly (Al-Duqm) and the south (Salalah). Investigating the socioeconomic, cultural and systemic factors that may lead to the spread of COVID-19 among migrants is important for developing and monitoring targeted preventive and intervention strategies for reduce transmission of the disease. The results of this study can aid in understanding the dynamics of the disease among migrants and hence the processes controlling its spread among migrants over space and time. This can contribute in helping decision-makers to adopt more appropriate mitigation measures and actions to control the propagation of the disease in Oman and the other GCC countries.

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